Instituut Fysieke Veiligheid

Hydrogen cars in parking garages

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Foreword

More than eighteen months ago, when I found myself on the campus of the University of Technology in Delft, I also visited the recently completed parking garage near the sport foundation. The parking garage in question is a multilevel, aboveground parking garage, with considerable numbers of facade openings. My attention was particularly drawn to the sign at the entrance prohibiting both electric cars and hydrogen cars.

We published a report in the summer of 2020 on the safety of parking garages housing electric cars. Our conclusions were that the parking of electric cars in parking garages should not be automatically prohibited, and that it is worthwhile investigating the design of parking garages and thinking about possible additional safety measures.

Immediately following the publication of that report, the question emerged whether the same ideas also applied to hydrogen cars, or whether other further measures would be needed to be able to guarantee safety. To provide an answer to these questions, it is first essential to understand the subject matter, by acquiring new knowledge. This report represents that step in the process. Based on three event trees (for fire, collision and leakage), this report elaborates the development of incident scenarios with a hydrogen car. This has given us a greater insight into the effects (jet flame, explosion) of such scenarios.

Nonetheless, there are still numerous unresolved issues, such as a quantitative interpretation of the scale of the effects and the related probabilities. Against that background, in 2021 we will continue to carry out further research into the safety aspects of hydrogen cars. This work will primarily relate to the possibilities of risk management and incident control, specifically for the provision of assistance in difficult environments such as parking garages. The present study offers an excellent starting point. It in fact reflects the nature of all research: building on existing knowledge in order to achieve progress, step by step. In this case, to further investigate and to understand the safety consequences of alternatively powered vehicles and the related infrastructure.

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Lecturer for Energy and Transport Safety

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Summary

The Dutch Ministry of Infrastructure and Water Management (IenW) commissioned IFV to investigate the safety aspects of hydrogen cars in parking garages. Seven research questions were formulated, three of which will be answered in this part report, namely:

1. To what extent do incident scenarios involving hydrogen cars in parking garages (including involvement in fire) result in the release of hydrogen, and what are the resultant effects?
2. What are the determining conditions for the nature and scope of the effects?
3. What is known about the probability of the release of hydrogen in a parking garage and the probability of that released hydrogen being ignited?

Hydrogen can escape in a number of different ways: through the instantaneous failure of the hydrogen tank, through continuous leakage via the relief valve, or continuous release through a small opening. These outflows may be caused by a collision, a fire or an unrelated leak, for example through micro openings.

Event trees for fire, collision and leakage identify the order of the circumstances and events that lead to one of the three possible outcomes, namely a jet flame, an explosion or no effect. The event trees do not indicate the extent to which a jet flame or an explosion may occur.

Essential factors that determine the scale of a jet flame or an explosion are the environment in which the hydrogen car is located, and the conditions under which hydrogen escapes:

- In parking garages, the effects of a jet flame or an explosion are greater than in the open air. The presence and level of ventilation can however prevent the LFL[1] being reached in the event of the release of hydrogen.
- The outflow conditions, such as the quantity of hydrogen escaping, the hydrogen pressure, the size of the outflow opening and the direction of outflow to a considerable extent determine the size and direction of the jet flame or the size of the hydrogen cloud and the hydrogen concentration in that cloud. In designing a safely working hydrogen system, these factors must be taken into account. Research has shown that safety gains can be achieved by reducing the diameter of the TPRD[2] in combination with increasing the heat resistance of the hydrogen tank, or by developing a hydrogen tank that will leak small quantities of hydrogen in the event of a fire.

The extent to which a hydrogen car becomes involved in a fire is among other things determined by the thermal intensity (MW/m^2) of the fire acting on the hydrogen car. The higher the thermal intensity, the earlier a TPRD will be activated. It cannot be ruled out that when the TPRD is opened, the resulting jet flame results in the spread of fire to adjacent cars in a parking garage.

[1] LFL = Lower Flammability Limit. The LFL is the lowest concentration at which an inflammable gas is ignited and whereby the flame that occurs sustains itself.
[2] TPRD = Thermally Activated Pressure Device.

It is only possible to give an indication of the probability of hydrogen *escaping* from a hydrogen car in a parking garage, because as yet, hydrogen cars are so uncommon that no empirical data is available. On the basis of a qualitative comparison between hydrogen cars and conventional cars, the conclusion is that the probability of hydrogen escaping in a parking garage is not greater - and is probably even smaller - than the probability that fuel will escape from a conventional car, in the event that both types of vehicles are involved in the same type of incident.

Literature does however reveal major differences in terms of the *ignition probability* of hydrogen, such that a comparison with the ignition probabilities of conventional fuel is not possible. As a result, further research is needed to arrive at the necessary clarity.

Introduction

Background

Hydrogen is a gas with a very low density and because it is inflammable, hydrogen is considered a hazardous substance. The physical properties of hydrogen and the resultant behaviour are described in detail in literature and in reports (IFV, 2020a). The use of hydrogen in cars therefore leads to risks. These risks are different from the risks from surrounding cars which are driven by conventional fuels such as petroleum and diesel. Risk perception also plays a role; on one hand, the risks facing conventional cars have been known and understood by their users for many years; the same does not apply to hydrogen cars. On the other hand, hydrogen cars are required not to pose more risk than conventional cars (Dadashzadeh, 2018).

Much of the research undertaken into hydrogen cars relates to the hazard aspect of hydrogen, in other words the effects that can take place if hydrogen is released. In literature, the release of hydrogen, in those cases, is often the starting point and a fixed given. However, for policy makers, not only the effects of the release of hydrogen are important, but also the probability that those effects can occur, for example as a result of an accident involving a hydrogen car. Nonetheless, little research has been done on the probability of the accidental release of hydrogen from hydrogen cars. This certainly applies to parking garages; parking garages have recently become a subject of interest due to fires in which electrically driven vehicles were involved (IFV, 2020b). Although as yet there are very few hydrogen cars on the roads in the Netherlands, the possibility that these cars will also be parked in parking garages raises questions about safety.

Questions

The Dutch Ministry of Infrastructure and Water Management (IenW) commissioned the IFV to investigate the safety aspects of hydrogen cars in parking garages. The following research research questions were formulated:

1. To what extent do incident scenarios involving hydrogen cars in parking garages (including involvement in fire) result in the release of hydrogen, and what are the resultant effects?
2. What are the determining conditions for the nature and scope of the effects?
3. Are parking garages capable of withstanding the possible effects of those scenarios (temperature and overpressure)?
4. What combinations of existing scenarios (without hydrogen cars) and new scenarios (with hydrogen cars) are possible in parking garages?
5. What is known about the probability of the release of hydrogen in a parking garage and the probability of that released hydrogen being ignited?
6. Can a sprinkler installation or water mist system be used in the event of an incident involving a hydrogen car in a parking garage, to effectively limit the consequences?

7. Provide a description of how safety issues and safety policy with regard to LPG vehicles in parking garages were dealt with in the past.

These research research questions will be answered in two phases. In consultation with the Ministry, research research questions 1, 2 and 5 will be answered in this report, based on the importance of and close relationship between these questions.[3] The remaining research questions will be dealt with in future parts of this report.

Research method

To be able to answer the research research questions and to underpin the answers, a literature study was carried out which involved a search in the database of ScienceDirect, based on a number of search terms. The search terms consisted of combinations of two or more words that were required to appear in the title or the abstract of a publication. Examples of the search terms used were HYDROGEN, SAFETY, PARKING, GARAGE, IGNITION, RISK ANALYIS, PROBABILITIES and variations on these words. After studying the title and/or abstracts of the publications, one or more publications were selected for further study. Many publications are published in peer reviewed journals, the most important one being the *International Journal of Hydrogen Energy*.
In addition to the use of search terms, the 'snowball method' was used as well whereby articles are found based on references in publications. Finally, publications, articles and documents were obtained via contacts and via Internet searches using Google Search.

Scope

- This report relates to hydrogen cars using gaseous hydrogen. The use of liquid hydrogen is not discussed, because liquid hydrogen is not used in hydrogen cars.
- The hydrogen cars described in this report use hydrogen as the energy carrier: hydrogen is converted to generate electricity to drive an electric motor. Hydrogen can also be burned as fuel in an internal combustion engine, but the majority of hydrogen cars do not operate according to this principle, and are therefore not considered in this study.

Guide

This report starts with a brief description in chapter 2 of the workings of a hydrogen car. Chapters 3 and 4 describe the causes and effects, respectively, of the release of hydrogen from a hydrogen car. The determining conditions are discussed in Chapter 5. Chapter 6 describes the findings in literature about the probabilities of the release of hydrogen. Each chapter ends with a summary of the key aspects of that chapter.

[3] In the elaboration for question 5, the possibility has been included that hydrogen will be released without there being an incident with an external cause.

1 Description of a typical hydrogen car

A hydrogen car is a car that uses hydrogen to generate electricity to drive an electric motor. The drive system for a hydrogen car consists of the following components and subsystems (see also Figure 1.1):

- filler system
- hydrogen storage tank
- pipe system from hydrogen tank to fuel cell
- fuel cell
- electric motor

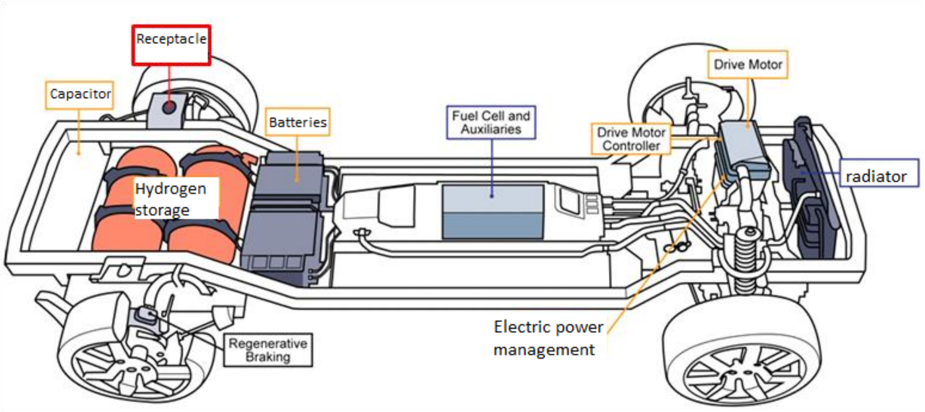


Figure 1.1 Schematic representation of a hydrogen car (UN, 2013)

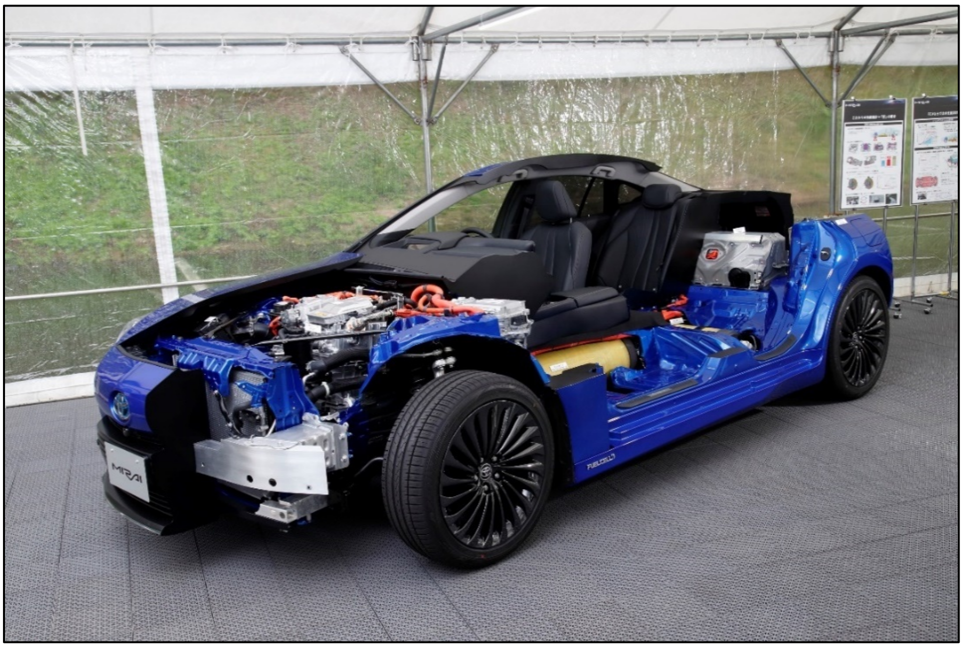


Figure 1.2 Cut-away view of Toyota Mirai (Newsroom Toyota)

1.1 Filler system

Hydrogen is delivered to hydrogen cars as a compressed gas. The refuelling nozzle and receptacle are designed in such a way that an enclosed system is created preventing hydrogen leaks. The receptacle includes a non-return valve that prevents the leakage of hydrogen when the refuelling nozzle is disconnected after refuelling.

1.2 Hydrogen tank

A hydrogen car contains one or more hydrogen tanks in which hydrogen is stored under high pressure (max. 700 bar). When the tank is filled, it contains more than 99.9% of all the hydrogen present in the hydrogen car (De Vos, 2020), see Table 1.1. The hydrogen tank, the filler system and the pipe system are separated by means of valves, the functioning of which is monitored whenever the hydrogen car is switched off.

To be able to resist the high pressures, a hydrogen tank is built in two layers. The inner layer prevents permeation while the outer tank provides the strength. The inner layer consists of a metal or a thermoplastic polymer, while the outer layer consists of a metal or a thermo-hardened polymer impregnated with a fibre-reinforced composite.

Table 1.1 Quantity of hydrogen in Hyundai Nexo (De Vos, 2020)

Description	Quantity
Capacity of hydrogen tanks Maximum hydrogen pressure in tanks Quantity of hydrogen in tanks	3 x 52 litres 700 bar 109,000 litres ≡ 9.11 kg
Capacity of pipes to fuel cell Hydrogen pressure in pipes Quantity of hydrogen in pipes	0.275 litres 17 bar 4.68 litres ≡ 0.39 g
Capacity of fuel cell (stack) Hydrogen pressure in fuel cell Quantity of hydrogen in fuel cell	5.17 litres 2.1 bar 10.85 litres ≡ 0.91 g

The tank wall of a hydrogen tank may be weakened when exposed to heat, which may cause the tank to burst. To prevent this, a hydrogen tank is equipped with a safety system that allows the controlled release of the tank's content, if the temperature in the vicinity of the tank rises too high. This is known as the TPRD (thermally activated pressure relief device). See also section 2.2.1.

The TPRD is fitted in a T-shaped component located at the end of a hydrogen tank. The T-shaped component consists of multiple valve systems, namely the TPRD, a non-return valve (check valve) to prevent hydrogen to escape via the filler pipe and an automatic shut-off valve that prevents hydrogen flowing to the fuel cell. See Figure 1.3 and Figure 1.4.

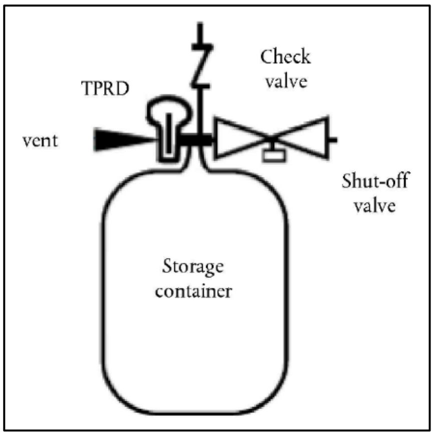
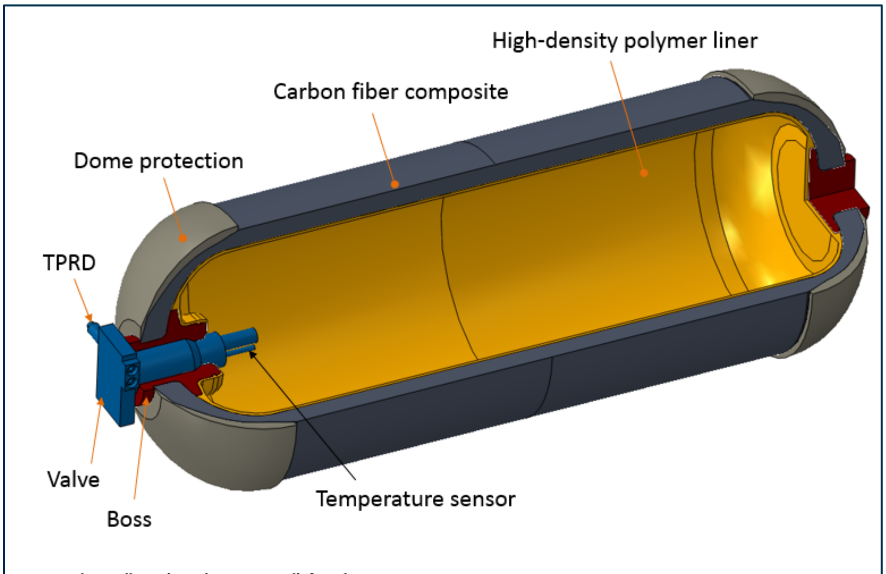


Figure 1.3 Structure of the valve system on a hydrogen tank (EU Regulation 134)



TPRD = Thermally Activated Pressure Relief Device

Figure 1.4 Example of a tank for the storage of gaseous hydrogen (Rivard et al, 2019)

To trigger the opening of a TPRD at 110 °C, a melting alloy or a glass bulb filled with a liquid can be used. A melting alloy is a (eutectic) metal alloy that melts at a relatively low temperature, causing the TPRD to open. In the case of a glass bulb, the liquid in the bulb expands if the temperature rises too high. This causes the bulb to break, and the TPRD is opened. Hydrogen cars today are equipped with TPRDs with a liquid-filled glass bulb.

1.3 Pipe system

Hydrogen passes from the hydrogen tank to the fuel cell, via a system of pipes. On entering the pipes, the pressure is lowered from 700 bar to less than 1 bar (overpressure) using pressure regulators. The pipe system is equipped with flow limiters to prevent the supply of hydrogen in the event of the pipe being damaged. If the pressure in the pipe system rises too high, for example due to an error in the pressure regulator, the content of the pipe is vented via overpressure valves.

1.4 Fuel cell

Multiple fuel cells form a stack that delivers sufficient power for the electric motor. In each fuel cell, hydrogen and oxygen are electrochemically converted into water:

Half reaction 1: $2\ H_2 \rightarrow 4\ H^+ + 4\ e^-$
Half reaction 2: $O_2 + 4\ H^+ + 4\ e^- \rightarrow 2\ H_2O$
Total: $2\ H_2 + O_2 \rightarrow 2\ H_2O$

The electrons formed in half reaction 1 are used in half reaction 2. The resultant electron flow is used to drive the electric motor.

1.5 Electric motor

The electrical power generated by the stack is delivered to the electric motor to drive the hydrogen car, with a battery acting as a buffer. This battery is also used to store the recovered braking energy. This literature study does not consider the safety aspects of batteries. For this aspect refer for example to (IFV, 2020b).

2 Causes

2.1 Introduction

This chapter answers the question to what extent incident scenarios involving hydrogen cars in parking garages result in the release of hydrogen (part one of research question 1). The effects that may arise from the various scenarios are described in chapter 3 (part two of research question 1).

Little reference is made to the causes of the release of hydrogen in literature. In many studies, the release of hydrogen is the starting point of research and in that sense, the cause of the release of hydrogen is not part of the research.

The vast majority of hydrogen in a hydrogen car is located in the tank (> 99.9 %). Given the high pressure at which this hydrogen is stored, the unintended release of hydrogen from the hydrogen tank can have serious consequences. Hydrogen can also escape from the pipes that lead from the hydrogen tank to the fuel cell. However, the consequences of this 'pipe scenario' will be relatively limited given the restricted capacity of these pipes. For that reason, the emphasis in this report is focused on the release of hydrogen from the hydrogen tank.

This study assumes that the correct choice of material ensures that the technical integrity of the fuel system in a hydrogen car is optimum, so that a cause such as hydrogen embrittlement is prevented (Barth et al, 2013; Ustolin et al, 2020).

2.2 Hydrogen release from the hydrogen tank

In principle, hydrogen can be released from the hydrogen tank in one of three ways:
1. instantaneous due to the failure of the hydrogen tank
2. continuous due to activation of the relief valve[4]
3. continuous due to a hydrogen leak

A fourth possibility is permeation, whereby hydrogen diffuses through the tank wall. In this case, the tank remains intact, and there is no opening through which hydrogen leaks, as referred to in possibility 3. However, the permeation process does not represent a safety risk, because permeation is severely restricted by the application of a thin layer of a specific material on the inside of the hydrogen tank (a liner) through which hydrogen is practically unable to pass. Studies have shown that the quantity of hydrogen that is released, even if such a layer is not present, is already negligibly small (Makarov et al, 2009; Adams et al, 2011).

2.2.1 Failure of the hydrogen tank

The most important causes of the failure of the hydrogen tank are (HySafe, 2005):

[4] The term 'continuous' is used in risk analyses and refers to a leak occurring over a longer period of time (RIVM, 2021).

- collision between the hydrogen car and an object or another vehicle
- failure of the relief valve causing the pressure in the tank to rise too high

Collision between the hydrogen car and an object or another vehicle
The hydrogen tank is designed to resist external impact, from outside. The requirements the hydrogen tank must satisfy and the tests it must undergo are described in EU Regulation 134 (EU, 2019) and in GTR 13 (UN, 2013). These include tests in which the hydrogen tank is fully or partially heated by a fire, and impact tests in which the hydrogen tank is dropped in different ways, from a specified height.
The hydrogen tank in a hydrogen car contains hydrogen at a pressure of 700 bar. Hydrogen tanks are designed to withstand pressures of at least 1575 bar, because legislation requires a safety factor of 2.25 (UN, 2013). This makes hydrogen tanks extremely strong and rigid and makes it less probable - but not impossible - for a hydrogen tank to fail due to external impact, for example a collision.

Failure of the relief valve (TPRD)
In order to be able to withstand high pressures, hydrogen tanks are made of composite materials. These are polymer materials reinforced with carbon fibres. The polymers degrade under the influence of heat, as a result of which the strength of the tank declines further the longer it is subjected to thermal radiation, for example in the event of fire. The most important measure for preventing degradation of the tank wall followed by rupture of the hydrogen tank is the thermally activated pressure relief device or TPRD (see Figure 1.4).

The TPRD is activated when the temperature near the TPRD rises to 110 °C. When the TPRD is activated, all the hydrogen present is released from the tank via an opening in the TPRD. In the event of ignition, a jet flame is created, but an explosion in the hydrogen tank is avoided (Cirrone, 2018).

It is possible that the TPRD fails to function, for example if the hydrogen tank is not fully but locally exposed to thermal radiation (Li et al, 2015) (Dadashzadeh et al, 2018). This can result in the explosion of the hydrogen tank, which is considered the most important risk of hydrogen cars (Dadashzadeh et al, 2018).

There are two developments which could prevent the failure of the TPRD in the future:
1. Ulster University has developed a hydrogen tank that will not fail if the tank is exposed to local thermal radiation from fire. This eradicates the need for the presence of a TPRD (Kashkarov, 2019).
2. An activation wire that runs over the entire length of a hydrogen tank. If the tank is exposed locally to thermal radiation, the wire at that point will shrink, causing the TPRD at the end of the tank to be opened (Dijkhof, 2021)

2.2.2 Activation of the TPRD
As described above, the TPRD is activated if the temperature in the immediate vicinity of the TPRD is too high, for example because the hydrogen tank is exposed directly to thermal radiation caused by a fire or because a fire is raging close to the hydrogen car and the heat from that fire activates the TPRD (UN, 2013).
Fires that could activate a TPRD can occur anywhere, and need not be related to outdoor carparks or parking garages. Fires can be subdivided into fires in the hydrogen car itself

(internal fires) and fires outside the hydrogen car (external fires). Possible causes of internal and external fires are (Olthof et al, 2011; Tamura et al, 2014; Li et al, 2015; Ren at al, 2019):

'Internal' fire activates TPRD

> Travelling fire: as a result of a fire in a carpark or parking garage, cars, including the hydrogen car, catch fire one by one
> Single-vehicle collision between the hydrogen car and an object or two-vehicle collision with another vehicle resulting in fire
> Setting alight of the hydrogen car
> Ignition of the hydrogen car, for example due to smoking in the car
> Auto-ignition due to a technical or electrical problem in the hydrogen car

External fire activates TPRD

> Fire in a nearby object or car (for example due to arson, short circuit, collision or problems with the engine (conventional car) or battery (electric car)).
> Fuel leak from nearby conventional car (for example due a collision) and the fuel spill ignites.
> Travelling fire: a nearby car burns as a result of a travelling fire.

'Travelling fires' are local fires that are caused by the transfer of fire from one object to another. Before the fire in one object has fully developed, the fire in another object is already extinguished. The fire as it were travels through a compartment but does not develop into a fire in the compartment itself (Mattheüs, 2018).

2.2.3 Hydrogen leak

If there is a hydrogen leak, the leak is generally around the valves or connections, because of the possible presence of micro openings. Although very small, these openings are large enough to allow the passage of hydrogen molecules (order of magnitude 10^{-11} m). For low-pressure natural gas systems in homes, this is a well-known phenomenon (Netbeheer Nederland, 2019) and the same is expected to apply to high-pressure systems with hydrogen. The worst case situation is when escaped hydrogen accumulates in an enclosed space in the car, with little to no ventilation. Ignition can then result in an explosion (Salva et al, 2012).[5]

2.3 Hydrogen release from the pipe system

The transport of hydrogen from the tank to the fuel cell takes place via a system of pipes, whereby the hydrogen pressure is reduced from 700 bar to 1 bar in two stages (UN, 2013). This system consists of connectors and valves from which hydrogen could potentially leak. Hydrogen leaks can occur for example as a result of the ageing of the system, poor maintenance or wrong material use (Molkov et al, 2019).

When a leak is detected by one of the sensors in a hydrogen car, the supply from the hydrogen tank is shut down, so that only the hydrogen contained in the pipe system can escape. This is not expected to result in an inflammable cloud, because the pipe system contains

[5] The presence of hydrogen in enclosed spaces in a hydrogen car is monitored using sensors. At 0.16 vol.% hydrogen, the hydrogen system is shut down.

little hydrogen. Furthermore, even if that hydrogen does escape, it is immediately diluted (Reuther et al, 2013).

In an Hyundai Nexo, the hydrogen system between the tank and the fuel cell contains approximately 15 litres of hydrogen. (By way of comparison: the three hydrogen tanks together contain more than 100,000 litres of compressed hydrogen). If these 15 litres were to be released at one time, the hydrogen concentration close to the car would be highest. However, because hydrogen rises and disperses in the environment, the concentration will rapidly decrease. This can be clearly explained with an example:

Imagine that 15 litres of hydrogen is released beneath the Hyundai Nexo and disperses around the car. The hydrogen concentration in the area 0.5 m around the car would then be 0.07 vol.%. This value is below the LFL for hydrogen (4 vol.%), the lowest concentration at which hydrogen ignites.

Vol.% Hyundai Nexo, = 4.7 m× 1.9 m × 1.6 m = 14.3 m^3 = 14,300 litres
Volume 0.5 m space around car = 5.7 m × 2.9 m × 2.1 m = 34.7 m^3 = 34,700 litres
Volume in which the hydrogen has dispersed = 34,700 l - 14,300 l = 20,400 litres
The hydrogen concentration is therefore (15l/20,400l) × 100% = 0.07 vol.%.

2.4 Summary

Hydrogen can be released in a number of different ways: through the instantaneous failure of the hydrogen tank, through continuous leakage via the relief valve, or continuous release through a small opening. These release flows may be the result of a collision, a fire or an unrelated leak, for example through micro openings.

3 Effects

3.1 Introduction

Chapter 2 indicated that collision, fire and leaks are the three main ways in which hydrogen can be released. With regard to fire and collision, the circumstances determine whether hydrogen actually is released: in the event of a collision, the force of the impact is for example a determining factor, while for a fire, the functioning of the TPRD is the determinant. Other circumstances determine whether the released hydrogen ignites and whether the ignition takes place immediately or is delayed. Using an event tree, the sequence of the events, the circumstances and the resulting effects can be demonstrated.

This chapter describes the event trees for collision, fire and leakage (the second part of research question 1). The event trees apply generically and not specifically to parking garages.

3.2 Event tree for a collision

Figure 3.1 Event tree for the release of hydrogen as a result of a collision (Ehrhart et al, 2020) shows the event tree for a collision. There are ten possible scenarios with three different effects (Ehrhart, 2020). The description of the scenarios assumes that the hydrogen car does not roll over[6]; as a result, any jet flame is aimed at the ground. If a hydrogen car does roll over, the jet flame can also be aimed horizontally or upwards.

1. The collision does not result in a fire or the release of hydrogen, because the impact of the collision is too small or because the safety systems function in the event of an accident. There may be material damage or personal injuries but no hydrogen-related effects.
2. The collision does not result in a fire, but hydrogen is released. This hydrogen is not ignited, for example because there is no ignition source or because the LFL is not reached. Given the strength of the hydrogen tank and the presence of valves that prevent the release of hydrogen from the hydrogen tank, this scenario is possible with a hydrogen pipe.
3. The collision does not result in a fire, but hydrogen is released, probably from a hydrogen pipe. The released hydrogen is ignited over time, resulting in an explosion as the worst case scenario.[7]
4. The collision does not result in a fire, but hydrogen is released, probably from a hydrogen pipe. The released hydrogen ignites immediately and generates a jet flame as long as hydrogen continues to be released from the pipe.

[6] This assumption is realistic because the possibility of a car rolling over in a parking garage is very small given the speed restrictions. See also section 5.4. GTR 13 specifies that the outflow direction is aimed downwards.

[7] The effects of the ignition of hydrogen depend on the hydrogen concentration. At concentrations between 4 - 9 vol.%, ignition takes place (cloud fire) but there is no explosion. Explosions take place at higher concentrations; between 9 - 18 vol.% in the form of deflagration and above 18 vol.% in the form of detonation. In the case of a detonation, the overpressures can be a factor of 20 times greater than with deflagration (IFV, 2020a).

5. A collision does result in a fire, but no hydrogen is released. The TPRD is not activated, for example because the fire is too far away or the fire does not last long enough. There are no hydrogen-related effects.
6. A collision does result in a fire, but no hydrogen is released. The TPRD is activated by the fire and functions correctly, releasing hydrogen which is immediately ignited by the fire. This results in a jet flame.
7. A collision does result in a fire, but no hydrogen is released. The TPRD is activated by the fire but fails to function. Due to a weakening of the tank wall, the tank tears open, and in the worst case results in an explosion.

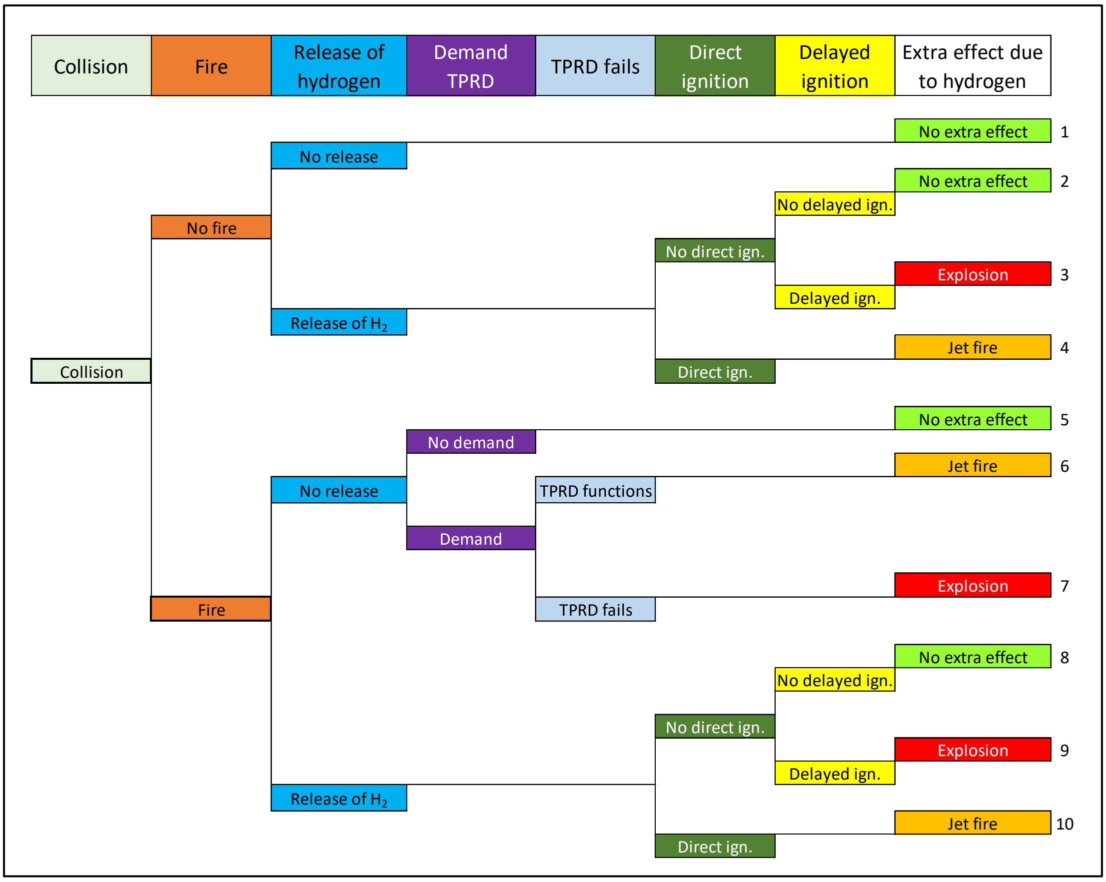


Figure 3.1 Event tree for the release of hydrogen as a result of a collision (Ehrhart et al, 2020)

8. A collision results in a fire and hydrogen is released, probably from a hydrogen pipe. However, the hydrogen does not ignite for example because the quantity is too small to exceed the LFL or because the escaping hydrogen is directed away from the fire. There are no hydrogen-related effects.
9. A collision results in a fire and hydrogen is released, probably from a hydrogen pipe. The ignition of the hydrogen is delayed and in the worst case results in an explosion.
10. A collision results in a fire and hydrogen is released, probably from a hydrogen pipe. The hydrogen ignites immediately and generates a jet flame as long as hydrogen continues to release from the pipe.

3.3 Event tree for a fire

Figure 3.2 shows the event tree for a fire (Ehrhart et al, 2020). The event tree is part of the event tree for collision, but is shown here separately for the sake of clarity. There are three possible scenarios with three different effects.

11. An internal or external fire does not result in activation of the TPRD, because the fire is too far away. No hydrogen is released from the hydrogen tank and there are no hydrogen-related effects. This scenario equates to scenario 5.
12. An internal or an external fire results in activation of the TPRD. The device functions, releasing hydrogen which is immediately ignited by the fire. This results in a jet flame. This scenario equates to scenario 6.
13. An internal or an external fire results in activation of the TPRD. The device fails to function. It is also possible that the hydrogen tank is locally exposed to thermal radiation, as a result of which the TPRD is not activated. Due to a weakening of the tank wall, the tank tears open, and in the worst case results in an explosion. This scenario equates to scenario 7.

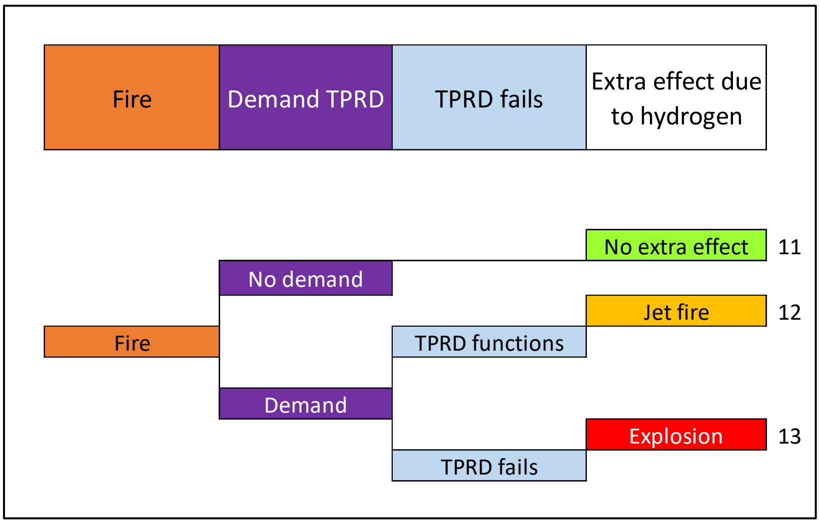


Figure 3.2 Event tree for the escape of hydrogen as a result of a fire (Ehrhart et al, 2020)

3.4 Event tree for a leakage

Figure 3.1 shows the event tree for a leakage (Ehrhart et al, 2020). The event tree is part of the event tree for collision, but is shown here separately for the sake of clarity. The term ‘release of hydrogen’ has been altered here to ‘leak’. There are three possible scenarios with three different effects.

14. Hydrogen is released, but fails to ignite entirely and disappears into the outside air. There are no hydrogen-related effects. This scenario equates to scenarios 2 and 8.
15. Hydrogen is released and ignites over time, and in the worst case can result in an explosion. This scenario equates to scenarios 3 and 9.
16. Hydrogen is released and ignites immediately, generating a jet flame as long as the hydrogen continues to be released. This scenario equates to scenarios 4 and 10.

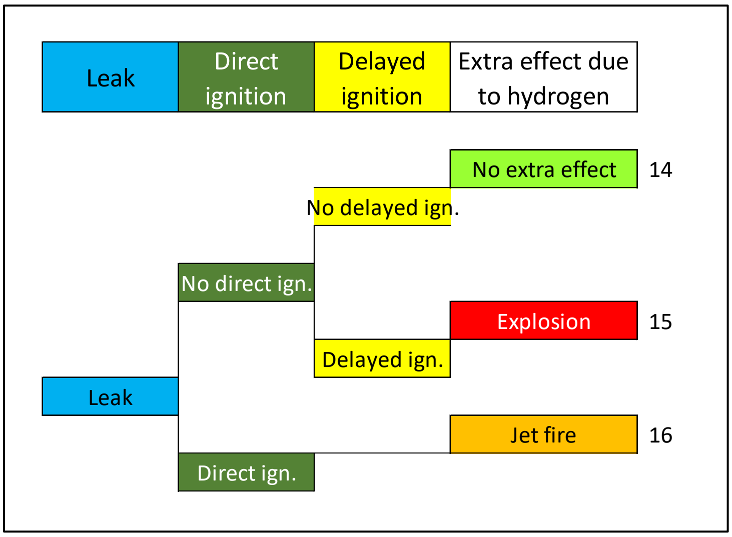


Figure 3.3 Event tree for the escape of hydrogen as a result of a leak (Ehrhart et al, 2020)

3.5 Discussion

The event trees for collision, fire and leakage show considerable overlap in terms of whether hydrogen is or is not released. The event trees provide an indication of the possible effects, but do not show under which circumstances hydrogen is released. However, to a considerable extent these circumstances determine the scale of the effects and as a consequence the potential damage. This is discussed in greater detail in Chapter 4.

The worst case situation is an explosion. An explosion can occur when the hydrogen tank bursts (scenarios 7 and 13) or the delayed ignition of a hydrogen cloud (scenarios 3, 9 and 15). If the hydrogen concentration is too low for an explosion, a cloud fire will occur upon ignition.

A jet flame is another scenario with considerable effects, but the effects of a jet flame are generally speaking less than those of an explosion, because the jet flame occurs in a single direction, while the overpressure effects of an explosion expand in all directions.

3.6 Summary

The event trees for fire, collision and leakage represent the sequence of circumstances and events that lead to the potential resultant effects. Important circumstances and events are the occurrence of fire, the release of hydrogen due to a collision or a fire, the activation and functioning of the TPRD and the (immediate or delayed) ignition or the non-ignition of hydrogen.

Eventually, there are three possible hydrogen-specific outcomes: a jet flame, an explosion or no effect. The latter effect refers to a situation in which no hydrogen is released or in which hydrogen is released but at a concentration that is too low to be able to ignite. The most serious situations are those in which an explosion or jet flame occurs. However, the extent to which these effects occur is not shown clearly by the event trees. To assess those effects, information is needed about the circumstances in which hydrogen can be released.

4 Determining conditions

4.1 Introduction

A fire, collision or leak is not an stand alone situation. As soon as one of these three initial events occurs, a range of follow-up events will take place. The sequence and extent of these follow-up events are determined by a large number of factors, and will impact the scale and severity of a jet flame or an explosion.

This chapter describes in outline the conditions that influence the effects of the release of hydrogen when a hydrogen car burns, collides or leaks in a parking garage (research question 2). The conditions described are categorised in the following themes:

- the surrounding in which the hydrogen car is located (parking garages)
- the way in which hydrogen is released
- the factors that influence the fire propagation

4.2 Surrounding

The event trees described in Chapter 3 apply in the open air, and are not specific to parking garages. The environment in which hydrogen is released, can however have a major influence on the seriousness and size of a jet flame or an explosion. In a parking garage, the consequences are greater than in the open air. Regarding jet flames, thermal radiation in parking garages is reflected, so that the thermal intensity of a jet flame in a parking garage has a greater reach than in the open air. For explosions, the overpressure in the open air reduces over distance because the surface area of the pressure wave increases as the distance to the source of ignition increases. In a parking garage, the surface area of the pressure wave cannot increase, due to the presence of the ceilings and walls. The overpressure from an explosion in a parking garage will therefore be greater than in the open air (Molkov et al, 2019).

4.2.1 Type of parking garage

Parking garages can be divided into open parking garages and enclosed parking garages. In the case of open parking garages, there is natural ventilation due to the presence of large openings to the outside air. Enclosed parking garages have no or far less connection to the outside air, making mechanical ventilation necessary in order to be able to guarantee the air quality (Jonkman, 2015). Open parking garages are located aboveground, while enclosed parking garages are generally underground.
If hydrogen is released in small quantities in a parking garage, it will mix with the air and disperse further either through mechanical or natural ventilation, and disappear into the open air. However, if hydrogen is released in large quantities - for example when the TPRD is opened - and is ignited immediately or after a delay, it obviously makes a major difference whether the hydrogen car is parked in an open parking garage or an enclosed parking garage. The more enclosed a space is, the higher the final hydrogen concentration can be, and the greater the potential effects following the ignition of the hydrogen cloud (Molkov et

al, 2019). It may be expected that in an enclosed parking garage, the consequences of the release and ignition of hydrogen will be greater than in an open parking garage.

4.2.2 Ventilation

Ventilation (natural as well as mechanical) in parking garages can have both a positive and a negative impact on the hydrogen concentration. In a positive sense, ventilation increases the speed and direction in which the hydrogen disperses, thereby reducing the hydrogen concentrations (Choi et al, 2013). On the other hand, ventilation means that the hydrogen cloud travels further and, if the ventilation direction is opposite to the outflow direction, local accumulation will occur. Moreover, ventilation accelerates the combustion of hydrogen, and that can result in greater overpressures (Molkov et al, 2019).

Standards specify that the ventilation or air change rate[8] of spaces must be such that the hydrogen concentration does not exceed 1 vol.% (Molkov et al, 2019). Certainly if the outflow rate of hydrogen is considerable, for example when the TPRD is opened, ventilation may be insufficient to maintain a low hydrogen concentration.

Using the following formula, it is possible to determine whether the ventilation system is capable of keeping the hydrogen concentration below the 1 vol.% level:

$$\text{vol.\% of hydrogen} = \frac{Q_{leak}}{Q_{ventilation} + Q_{leak}} \times 100\% \quad \text{where Q is measured in } m^3/min \qquad [1]$$

Imagine that a 1000 m^2 parking garage is ventilated at a rate of 0.0038 $m^3 \cdot s^{-1} \cdot m^{-2}$ or 228 m^3 per minute (= $Q_{ventilatiion}$) (ICC, 2018). In this situation, a leak of 2 m^3/min (= Q_{leak}) results in a hydrogen concentration of 0.9 vol.% which is below the set requirement of 1 vol.%.

This formula is a rough approximation, because it assumes that all escaping hydrogen disperses throughout the parking garage and that the concentration is the same throughout

4.3 Outflow

The following aspects play an important role in the outflow and as a consequence, the dispersion of hydrogen.

4.3.1 The capacity of the system containing hydrogen

The system containing hydrogen in a hydrogen car consists of the hydrogen tank, the pipes from the filling point to the hydrogen tank and the pipes from the hydrogen tank to the fuel cell. The various parts of this system can be sealed off using safety or other valves.
The hydrogen tank contains the majority of the hydrogen and the extent to which the tank is filled determines the outflow time. With a full tank, in the case of immediate ignition, the jet flame will last longer. In the case of delayed ignition, the hydrogen cloud will be able to expand further and achieve higher concentrations. If the hydrogen cloud subsequently ignites, the effects may be greater than if the hydrogen tank had been only half filled.
The pipes from the hydrogen tank to the fuel cell are at low pressure and contain little hydrogen. If this hydrogen is released, the effects will be limited (see also section 2.3).

[8] The ventilation or air change rate is a measurement for the ventilation in a space, and is the figure that indicates how many times per hour the space is supplied with fresh air.

4.3.2 Outflow direction

The outflow direction of the hydrogen affects the extent to which a jet flame can radiate heat towards persons or objects. The heat from a jet flame pointing upwards will spread less far at ground level than a jet flame that is directed horizontally. In a parking garage, these differences are expected to be considerably less clear, given the presence of obstacles such as ceilings, floors, walls and cars that interrupt the course of the jet flame.

Similar properties apply to a hydrogen cloud. The distance (in the horizontal plane) covered by a hydrogen cloud in an open space, if the outflow is directed upward, is smaller than if the outflow is directed horizontally. In parking garages however, dispersion is heavily influenced by the presence of natural or mechanical ventilation, and the presence of obstacles. Obstacles such as walls and ceilings will result in the local accumulation of hydrogen. It is therefore not possible to determine in advance what effect the outflow direction will have on dispersion, because dispersion also depends on numerous other factors.

Because practical experiments with hydrogen are costly, computer simulations have been used to investigate the dispersion behaviour of hydrogen in a small parking garage (Hussein et al, 2020). This study considered the angle at which hydrogen is released from the TPRD, through an outflow diameter of 2 mm, see Figure 4.1. If hydrogen is released at an angle of 0° (in relation to ground level), a flammable cloud is formed at the location of the hydrogen car, whereas at an outflow angle of 30° or 45°, the cloud is pushed further away. This is a favourable situation if the driver and other occupants are forced to flee.

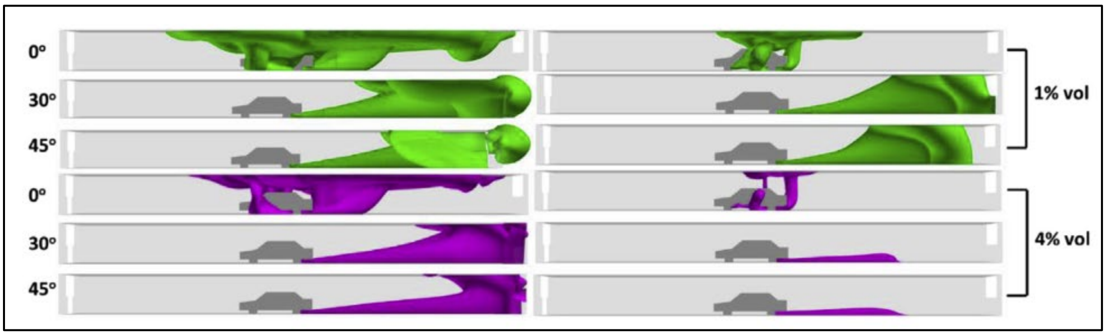


Figure 4.1 Illustrations of dispersion calculations in a small, half-open parking garage in the event of the outflow of hydrogen from a hydrogen tank at 700 bar, with a TPRD diameter of 2 mm (left) and 0.5 mm (right). The hydrogen concentrations after 20 seconds are shown for 1 vol.% H_2 (green) and 4 vol.% H_2 (purple) for three different outflow directions. Mechanical ventilation was not incorporated in the simulations (Hussein et al, 2020)

In the case of a TPRD with a diameter of 0.5 mm, releases upwards and downwards were simulated, see Figure 4.2. The downward outflow (left in the figure) creates a hydrogen cloud in, around and above the hydrogen car, after 20 seconds. This is unfavourable for occupants if they have to flee. The upward outflow (right in the figure) produces a hydrogen cloud below the ceiling of the parking garage..

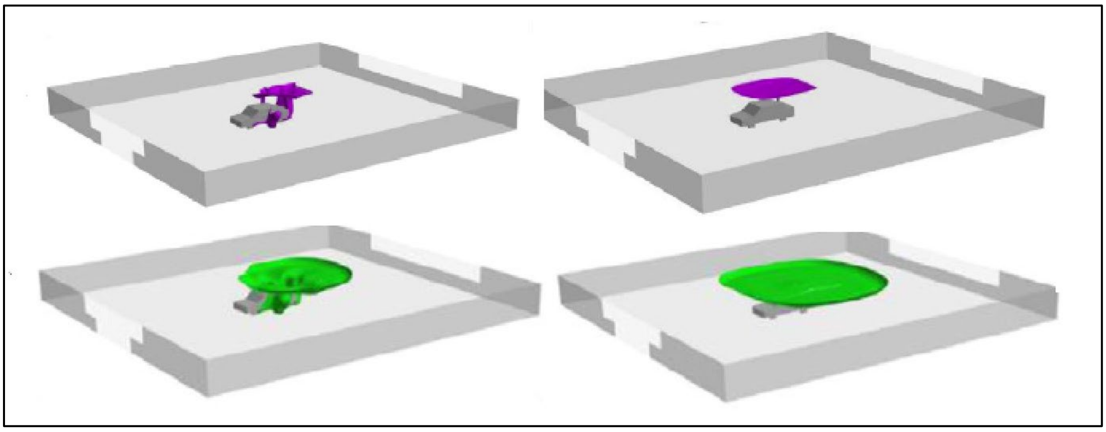


Figure 4.2 Illustrations of dispersion calculations in a small, half-open parking garage from a hydrogen tank at 700 bar with a TPRD diameter of 0.5 mm, with a outflow direction downwards (left in the figure) and upwards (right in the figure). The hydrogen concentrations are shown after 20 seconds for 1 vol.% (green) and 4 vol.% (purple). The simulations were not subject to any mechanical ventilation (Hussein et al, 2020)

4.3.3 Hole size

In the event of a leak, the size of the opening (the hole) determines the quantity of hydrogen that is released, and consequently the duration and size of the released. The smaller the opening, the less hydrogen is released, and the smaller the hydrogen cloud. This can be taken into account in designing the TPRD, but because it takes longer for the hydrogen tank to empty (see   ), the time to failure of the hydrogen tank must be improved. This is known as the Fire Resistance Rate (FRR, see section 4.4).

4.3.4 Hydrogen tank material

In the HyTunnel project it is believed that it is (far) more efficient to develop an inherently safe hydrogen car, than to invest 'heavily' in adapting existing buildings and taking preventive measures in those buildings (Molkov et al, 2019). For that reason, research has been conducted into the material from which the hydrogen tank is made, and a hydrogen tank has been developed that is able to leak hydrogen in the event of fire.[9] The quantity of hydrogen that can be released from the hydrogen tank equates to the leak flow from a TPRD with a diameter of 0.2 - 0.3 mm. This ensures that the size of the flammable cloud is made far smaller or ensures that the hydrogen concentrations can be kept below the LFL (Molkov, 2018; Hussein, 2020). Hydrogen tanks of this kind are still currently in the research stage and have not yet been used in the today's hydrogen cars (Dijkhof, 2021).

4.3.5 Hydrogen pressure

In the event of a leak, the hydrogen pressure is another determining factor for the quantity of hydrogen that is released. The higher the pressure, the faster the outflow speed and the more hydrogen is released. The largest outflow occurs at the start, because the pressure in the hydrogen tank is then at its highest, and falls as soon as hydrogen starts to release.

[9] This hydrogen tank is known as an LNB tank: Leak-No-Burst.

The diameter is a vital parameter in the design of the TPRD. The diameter of the TPRD is partly determined by the capacity of the hydrogen tank: the larger the capacity of the hydrogen tank, the larger the diameter of the TPRD must be in order to allow the contents of the hydrogen tank to be released, in time. The disadvantage of a TPRD with a large diameter is that a jet flame that occurs will be large. The advantage of a small diameter is that the quantity of hydrogen that can be released per time unit is far smaller, as a consequence of which the LFL may not even be reached. On the other hand, the hydrogen tank must be resistant to thermal radiation for longer (Hussein et al, 2020).

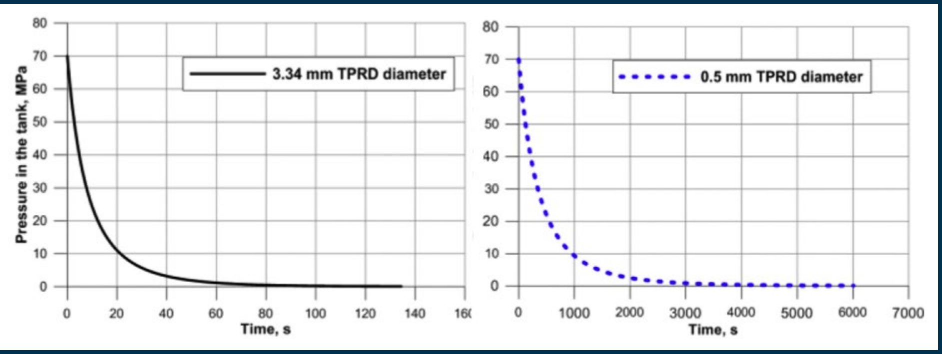


Figure 4.3 The pressure drop in a hydrogen tank of 117 litres as a function of time for two different TPRD diameters (Hussein et al, 2020)

The diameters of the TPRDs in hydrogen cars are confidential (Dijkhof, 2021). It is indicated in literature that the diameter of TPRDs in 2019 was around 2-3 mm, as compared with 6 mm in earlier years. The reason for switching to smaller diameters was the fact that the length of the hydrogen jet flame is proportional to the diameter of the TPRD. In other words; a smaller TPRD diameter results in a shorter jet flame and as a consequence leads to less damage (Molkov et al, 2019).

4.4 Fire spread

This section describes a number of aspects that play an important role in the speed with which fire can spread from one car to another.

4.4.1 Intensity of the thermal radiation

The intensity of the heat radiated on a hydrogen tank (the Heat Release Rate (HRR) per m^2) determines the time it takes until the hydrogen tank fails (FRR). Tests on hydrogen tanks not fitted with a TPRD showed that as the intensity of the fire increases, so the FRR decreases, see Figure 4.4 (Molkov et al, 2019).

The amount of heat released in a car fire (HRR) increases when a TPRD is activated and a jet flame arises. In experiments in which the maximum energy released was 3 MW, the amount of energy increased to a maximum of 29 MW following the opening of a TPRD with a diameter of 3 mm, see Figure 4.5. Reducing the diameter of the TPRD ensures that this effect is almost entirely eradicated.

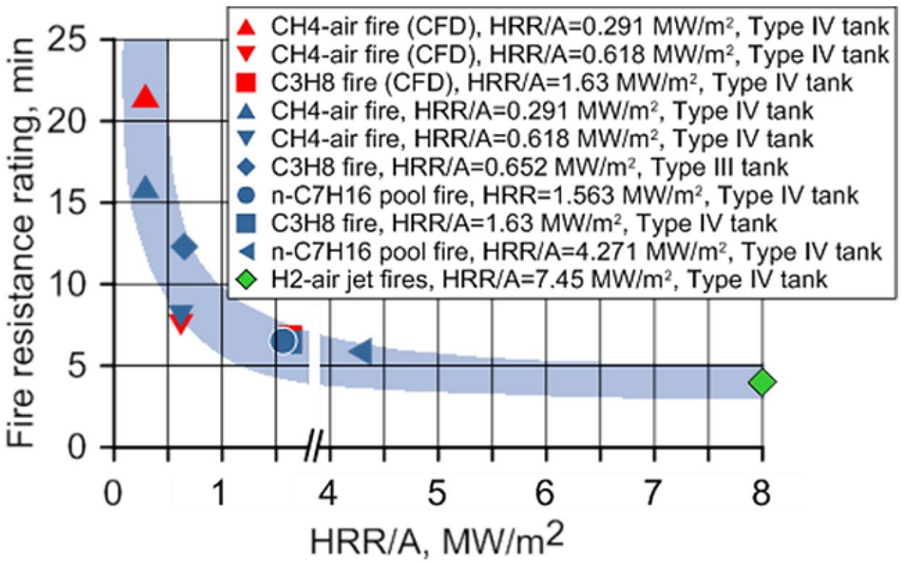


Figure 4.4 Time to failure of the hydrogen tank (FRR) as a function of the amount of heat *(Heat Release Rate)* per m^2 (Molkov et al, 2019)

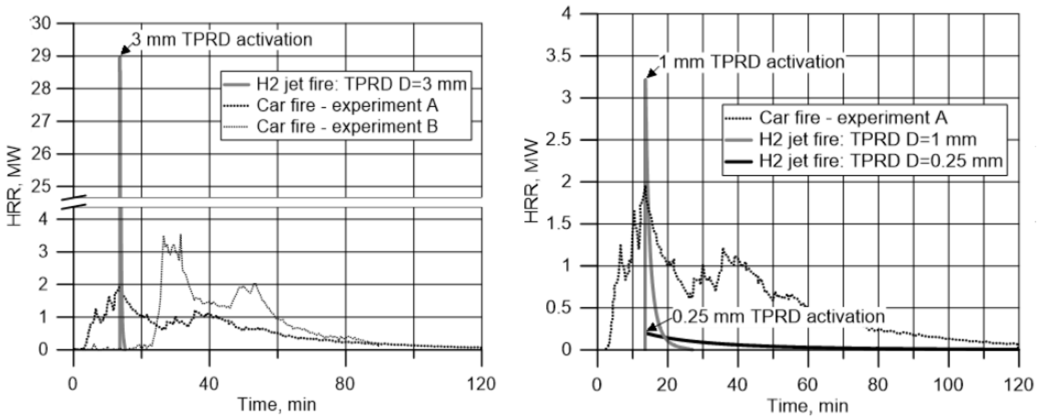


Figure 4.5 The amount of heat (HRR) released during a car fire (experiments A and B) and when a 3 mm TPRD (left) or a 0.25 mm or 1 mm TPRD (right) result in a jet flame (Molkov et al, 2019)

It is not said that opening a TPRD and the occurrence of a jet flame will by definition encourage the spread of fire. In experiments in the open air, a TPRD with a diameter of 4.2 mm was manually activated after 30 minutes, creating a jet flame which was aimed at the ground, and which, as a result of deflection, caused a sea of flame beneath the hydrogen car. However, these flames did not reach the conventional car parked nearby (separation distance 0.85 m). The conventional car was only set alight after 58 minutes, by which time the hydrogen car had almost entirely burned out, see Figure 4.6 (Tamura, 2014). The reason why the adjacent conventional car was not set alight was that the flames were deflected upwards as a result of the lighter-than-air property of hydrogen; consequently they did not reach the conventional car (see Figure 4.7) and that the heat radiation was insufficient to cause the adjacent car to ignite.
As compared with the open air, in a parking garage, the heat from the jet flame is less able to escape, as a result of which the immediate environment is heated further. Consequently, it cannot be ruled out that in a parking garage, the fire in a hydrogen car will spread to an adjacent car. This is indeed demonstrated in a first simulation with a TPRD of 5 mm (Markert

et al, 2019). If the adjacent car were a hydrogen car, in theory, the TPRD of that hydrogen tank would be activated (Tamura et al, 2014). However, there is as yet no description in literature of experiments in parking garages to investigate fire spread from hydrogen cars to other cars.

Literature suggests that the diameter of TPRDs has been reduced over the past few years. As a result, jet flames are smaller and the effects described above may also be smaller. However, as long as the diameter of the TPRD remains confidential, and no new experiments are described, the possibility of fire spread in parking garages from hydrogen cars to other cars cannot be excluded.

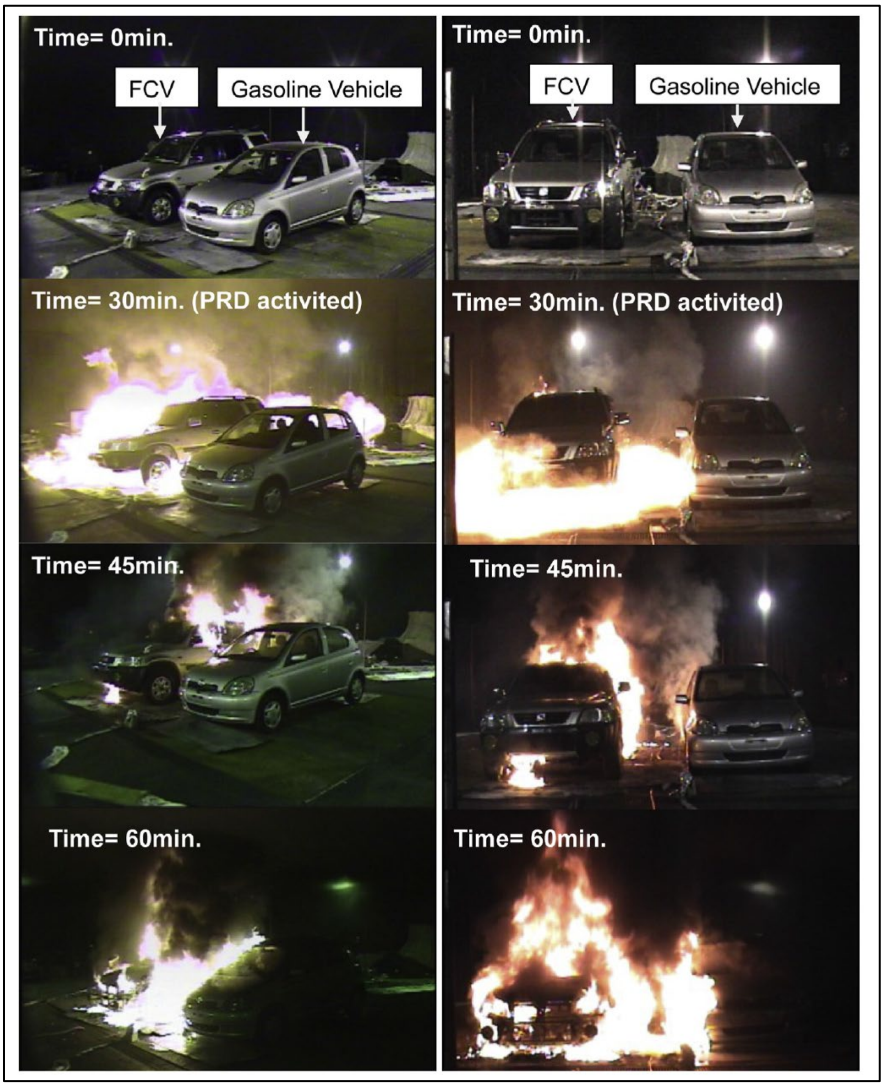


Figure 4.6 Photographs of experiment (Tamura et al, 2014)

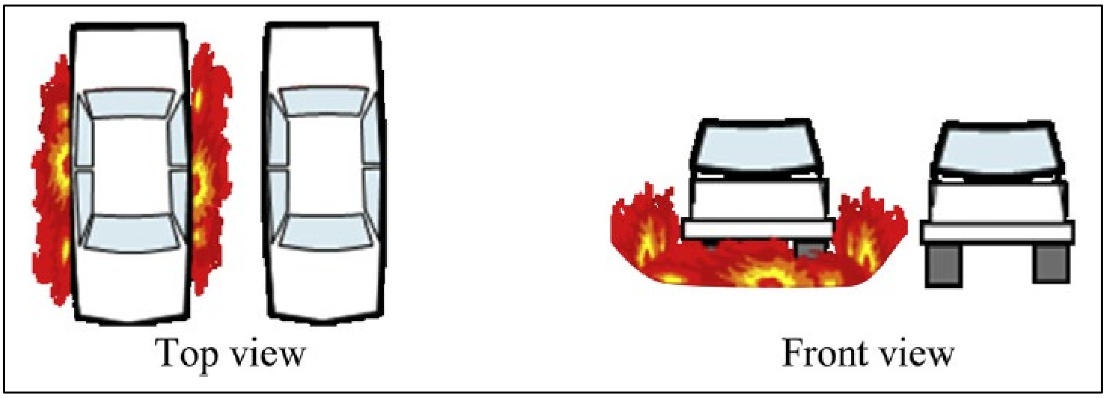


Figure 4.7 Deflection of hydrogen jet flame following activation of the TPRD (Tamura et al, 2014)

4.4.2 The size of the car

The quantity of heat radiated onto the hydrogen car is important in determining the time to failure of the hydrogen tank (FRR). It would be expected that a larger and heavier car would generate more heat, but no clear relationship has been identified between the weight class of the car and the HRR (NFPA, 2020).
The HRR for cars is between 2 and 9 MW. For a car that is 4 m long and 1.5 m high, that is subjected to heat radiation, the resultant thermal intensity is between 0.3 and 1.5 MW/m^2. If the TPRD were then not to function, it would take between 5 and 15 minutes before the hydrogen tank fails.

4.4.3 Plastic

For reasons of weight saving, and to make specific shapes possible, modern cars contain an ever growing share of plastic. In terms of weight, the share of plastic in cars has reached around 10% (NFPA, 2020). The increase in the use of plastic in cars has a number of consequences:

- an increase in the amount of heat released in the event of a fire
- cars ignite sooner and burn more quickly (NFPA, 2020).

4.5 Summary

The release of hydrogen will result in a jet flame if ignition takes place immediately, and in an explosion if ignition is delayed. The extent and severity of these effects are influenced by numerous factors. One essential factor is the surrounding in which the hydrogen is released. In parking garages, the consequences of a jet flame or an explosion are larger than in the open air. The presence and level of ventilation can however prevent the LFL being reached when hydrogen is released.

The outflow conditions also play a major role in the extent to which hydrogen is released and in the dispersion behaviour. These conditions refer to the capacity of the system containing hydrogen, the hydrogen pressure, the hole size, the material of which the hydrogen tank is made and the outflow direction.

Research has shown that safety can be further improved by reducing the diameter of the TPRD in combination with increasing the heat resistance of the hydrogen tank, or by developing a hydrogen tank that is able to leak small quantities of hydrogen when exposed to a fire.

The extent to which a hydrogen car becomes involved in a fire is among others determined by the intensity of the fire. The higher the thermal intensity, the sooner a TPRD will be activated. The jet flame that arises when the TPRD is opened does not necessarily result in fire spread to adjacent cars.

5 Probabilities

5.1 Introduction

Risk is the term used to describe the combination of the probabilities of unintended events and the effects of those events. Risks come in all shapes and sizes: there are events with small probabilities and large effects and there are events with large probabilities and small effects. How great a risk may be and whether it is acceptable, are not always laid down in laws and regulations, and the situation differs from domain to domain.
Much scientific research is being carried out into the effects of the release of hydrogen and the circumstances in which those effects occur; to determine the risks however, it is just as important to get a feeling for the probabilities and odds. There is not yet any such thing as 'the' probability or 'the' odds of hydrogen incident scenarios for passenger cars, because there are many uncertainties due to a lack of data.[10] So far, there are too few hydrogen cars with which too few incidents occur in order to derive statistically reliable probabilities.[11] Every event in the event trees in Figure 3.1 Event tree for the release of hydrogen as a result of a collision (Ehrhart et al, 2020) - Figure 3.1 has its own uncertainties so that the probability of a jet flame, explosion or no effect is effectively a probability with a (considerable) margin of uncertainty.

This chapter describes the information contained in literature about the probabilities and odds (research question 5) of the events listed below. These are events from the event trees in Figure 3.1 to Figure 3.1:

- collision
- fire
- release of hydrogen
- activation and failure of TPRD
- ignition

As far as possible, an indication will be given of how the data for hydrogen cars relate to data for conventional cars. As previously stated, the qualitative comparison results more in an impression that an absolute certainty.

10 *'The probability of being affected by a flood is once every 10,000 years:'* The term 'probability' here is an absolute number that indicates how often an event can occur per time unit. The term 'odds' refers to the ratio between the number of times an occurrence can take place as compared with the total number of possibilities. The odds are therefore a number between 0 and 1. For example the odds that rolling a 2 on a dice are 0.17 (1/6).

11 At the end of July 2020, there were 261 hydrogen cars in the Netherlands, out of almost 8.7 million passenger cars; that equates to 0.003%.

5.2 Collision

5.2.1 Conventional car

The probability of an accident[12] involving a conventional car in the Netherlands is estimated at 7.7×10^{-3} per car per year. This number must be seen as an order of magnitude and is based on the following figures:

> 73,000 accidents involving cars and light commercial vehicles in the Netherlands in 2017 (RWS, 2017)

> 9.4 million cars and commercial vehicles in the Netherlands in 2017 (Environmental Data Compendium, 2018)

5.2.2 The causes of a collision involving a conventional car

According to American research, human failure is the main cause of accidents involving vehicles (NHTSA, 2015). Around 94% of accidents are caused by the driver, while the other causes are the failure of the vehicle itself and environmental factors[13] (each accounting for 2%). The direct cause of 2% of the accidents investigated in America, is unknown. Collisions in parking garages mainly occur during special manoeuvres by vehicles, and human failure is the underlying cause (Webb, 2020).

5.2.3 Hydrogen cars versus conventional cars

In the Netherlands, at present, there are 261 hydrogen cars on the road (EVConsult, 2020), of which as far as we know only one has been involved in an accident (Waterstofmagazine, n.b.).[14] Statistically, these numbers are too small to produce reliable accident probabilities for hydrogen cars.

If it is assumed that human failure is the primary cause of an accident involving a vehicle, and assuming that the behaviour of the driver is not dependent on the type of vehicle he/she is driving, then the probability of an accident involving a hydrogen car will be comparable to the probability of an accident involving a conventional car. The term ‘comparable’ means that there may be differences, but in terms of order of magnitude, the probabilities are equal, and there is little difference statistically.

5.3 Fire

5.3.1 Conventional car

The probability of a fire in a conventional car in the Netherlands is estimated at 4.3×10^{-4} per car per year. This number must be seen as an order of magnitude and is based on the following figures:

> 4004 car fires in the Netherlands in 2017 (CVS, 2020)

> 9.4 million passenger cars and light commercial vehicles in the Netherlands in 2017 (CLO, 2018)

A limited number of these fires take place in parking garages. Between 2006 and 2015, on average around 5 fires per year took place in parking garages in the Netherlands (BZK,

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12 In this report, an accident is defined as an incident involving one or more vehicles. An accident is in many cases a collision, which is why data relating to accidents has been applied to collisions.

13 Examples are weather conditions or a poor road surface.

14 No information is available about this accident such that the precise course of events cannot be identified.

2020). It is unknown how many vehicles were involved. The cause was not always a vehicle fire. If it is assumed that all fires in parking garages are vehicle fires, and that one vehicle is involved in each fire[15], the probability that a conventional car would burn in a parking garage is 5.3×10^{-7} per car per year[16] (5/9,400,000) and the proportion of car fires in parking garages is 0.12% (5/4004) of the total number of car fires.

Data from the NFPA indicate that in America, 1% of all vehicle fires take place in storage locations. This includes showrooms but also parking garages (NFPA, 2020a). If the figures from the NFPA were applied to the Dutch situation, there would be around 40 car fires every year in storage locations (1% of 4004). Because the proportion of parking garages is unknown, this number must be considered as the upper limit. The upper limit for the probability of a burning conventional car in a parking garage is therefore 4.3×10^{-6} per year (40/9,400,000).

Figures from New Zealand indicate that in the period 2005-2012, the probability of a vehicle catching fire in a parking garage was equal to 1.2×10^{-6} per year. For the period 1997-2003, this was 4.8×10^{-6} per year (Tohir, 2014). Literature does not show the cause of this reduction by a factor of 4.

5.3.2 Causes of internal fire

The main causes of an internal fire in conventional cars are fuel leaks, faults in the electrical circuit of a car, an overheated engine, an overheated catalytic converter, arson, collisions[17], poor maintenance and design errors (NFPA, 2020b) (Mattheüs, 2016). For electric cars, battery fires are also known as a cause of internal fires (IFV, 2020b).
Deliberately setting a car on fire causes a quarter of all car fires in parking garage (Li, 2004; Wijnhoven, 2009). The presence of supervision and/or cameras reduces the probability of arson.

5.3.3 Causes of external fire

A vehicle parked in a parking garage can catch fire due to direct flame contact or heat radiation, if a fire is burning nearby. This may be a fire in a vehicle parked nearby (travelling fire) or for example a waste container which has been set alight (Mattheüs, 2018; BZK, 2020).
The probability of fires of this kind in parking garages increases because more polymers are being used in cars and cars are becoming larger (NFPA, 2020). Because of the low ignition temperature of rubber, the tyres generally ignite first.

5.3.4 Hydrogen cars versus conventional cars

Hydrogen cars have no combustion engine and no exhaust system with catalytic converters. Fire due to the failure of one of these components is therefore excluded in the case of hydrogen cars. The release of hydrogen from the hydrogen system is a possibility, see section 5.4.

On the basis of the collected data, the probability of an internal fire for hydrogen cars appears to be smaller than for conventional cars. The probability of *being involved* in an external fire will be just as great for hydrogen cars as for conventional cars. This means that the probability of a hydrogen car becoming involved in a fire in a parking garage is smaller than the probability for a conventional car.

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15 The vast majority of fires in parking garages involve just one car (Tohir, 2014).

16 It would be more accurate to calculate the probability of a car fire per visit to a parking garage, but due to a lack of data this is not possible. In literature, a value of 1.71×10^{-7} per visit is given for this situation (Li, 2004).

17 This relates to vehicle fires on motorways and roads.

5.4 Release of hydrogen

5.4.1 Conventional car

With respect to leaks: in the case of a conventional car, fuel can leak from the tank or the fuel pipe, for example due to poor maintenance or the age of the fuel system. This can happen anywhere and the probability of it happening in a parking garage is no different than if the vehicle is located elsewhere.

With respect to collision: fuel leaks due to a collision are less likely in a parking garage than outside. Vehicles have crumple zones that are designed to absorb the force of the collision, and to protect the occupants and important parts of the vehicle. In addition, in a parking garage, the maximum speed is 15 km per hour (RVV, 1990).

With respect to fire: many conventional cars have a plastic fuel tank. In the event of a pool fire beneath the car, the plastic fuel tank will start to leak within 2 to 5 minutes, and contribute to the pool fire (NFPA, 2020).

5.4.2 Hydrogen car vs. conventional car

With respect to leaks: a cause of failure such as aging is limited in hydrogen cars by the requirement that the hydrogen system may not be older than 15 years. For conventional cars, there is no age requirement for the fuel system. In addition, the integrity of the entire hydrogen system is checked during service inspections (UN, 2013), the pressure in the various parts of the hydrogen system is monitored and a hydrogen car is equipped with hydrogen detection, at various points. If a hydrogen leak is observed, the hydrogen car switches off (De Vos, 2020).

With respect to collision: hydrogen tanks are stronger than fuel tanks in conventional cars because hydrogen in hydrogen tanks is stored under high pressure (maximum 700 bar overpressure), while petrol and diesel are stored at ambient pressure (0 bar overpressure). Nevertheless, a hydrogen tank must be able to withstand far higher pressures than 700 bar (more than 1500 bar, see section 2.2.1). It is expected that due to their strength and rigidity, hydrogen tanks will not only be resistant to the internal pressure in the tank, but also to external impact from a collision (see also block on next page). Moreover, safety measures are built in in hydrogen cars, to halt the release of hydrogen in the event of a collision or the hydrogen car turning over, so that any outflow of hydrogen outside the car is prevented (UN, 2013).

With respect to fire: hydrogen cars have a plastic tank that will degrade under the influence of heat. In that respect, conventional cars and hydrogen cars are no different. The consequences for a hydrogen car, however, are greater than for a conventional car, hence the presence of a TPRD to allow the hydrogen to be released in a controlled manner, in the event of fire.

Based on these considerations, the probability of the release of hydrogen is considered small, and this probability is expected to be smaller than the probability of the release of fuel from a conventional car.

In the event of a collision involving a hydrogen car, the moving car suddenly comes to a standstill. The forces acting on the hydrogen car are described with the formula:

$$F = m \times a \qquad [2]$$

The force F (N) is equal to the mass m (kg) times the acceleration a (m/s^2). In the event of a collision, the acceleration is the speed difference before and after the collision, divided by the time it takes to become stationary:

$$a = \Delta v / \Delta t \qquad [3]$$

The combination of formulae [2] and [3] results in:

$$F = m \times \Delta v / \Delta t \qquad [4]$$

If a car travelling at 15 km/hour (4.2 m/s) collides with a hydrogen tank of 25 kg, and the duration of the collision is 0.01 s, the force acting on the hydrogen tank is[18]:

$$F = 25 \times 4.2/0.01 = 10{,}500 \text{ N}$$

This force is spread over the contact surface with the hydrogen tank. Assuming that the contact surface is 0.3 m^2, the force acting on the contact surface of the hydrogen tank is:

$$P = F/A = 10{,}500/0.3 = 35{,}000 \text{ N/m}^2 = 0.35 \text{ bar}$$

It is not expected that a hydrogen tank that is capable of withstanding an internal pressure of more than 1500 bar will fail due to an external pressure of less than 1 bar.

5.5 Activation and failure of the TPRD

Vehicles that run on LPG or CNG have a facility on the fuel tank that allows the release of the contents of the tank, if the tank pressure becomes too high. A fuel tank for petrol or diesel does not have such a safety facility, because the effects of the release of petrol or diesel are smaller than the effects that may arise if hydrogen is released.

Hydrogen tanks of hydrogen cars are equipped with a TPRD as safety measure to prevent a too large increase of pressure in the tank due to heat radiation (see section 2.2.1). Despite the fact that TPRDs are tested for type approvals, the probability of failure is not zero. A TPRD can fail in one of two ways:

- the TPRD opens in the absence of a fire nearby (unintended opening)
- the TPRD fails to open in the presence of a fire nearby.

Almost no data are available in literature about either of these failure probabilities and consultation with experts also provided no information (De Vos, 2021) (Dijkhof, 2021). The information in this section is obtained from a limited number of publications. In these publications, data from comparable systems (analogons) are used due to the lack of data. This is not an unusual method (RIVM, 2012).

5.5.1 Opening of the TPRD in the absence of fire

There is a probability that a TPRD will open while there is no fire that has activated the TPRD. This may take place in serious collisions, but the cause of the activation of a TPRD cannot always be determined (Sunderland, 2008) (Dadashzadeh, 2018). Given the low maximum speed in parking garages (15 km/hour), high-impact collisions are not expected.

[18] This takes no account of the crumple zone that absorbs part of the impact.

In literature, the odds of a TPRD being activated in the absence of a fire are estimated at 6.0×10^{-3}, in other words of the thousand TPRDs, six will open. In the absence of sound data, this value is based on data from safety systems in the process industry, whereby the systems respond to pressure change rather than temperature (Saw, 2016), the so-called pressure relief devices (PRD). This value is almost three times as high as the value (2.2×10^{-3}) discovered for the failure of the PRD in CNG tanks in vehicles in the absence of fire (Berghmans, 2014).

From a scientific point of view, it is incorrect to use PRDs from the process industry as an analogon for TPRDs in hydrogen cars, because there are too many differences between the two systems (design, maintenance regime, process conditions, intensity of use, etc.). The only matching factor is the *function* of the two systems. The PRD in a CNG tank is also not a good analogon but does share more common factors with the TPRD in a hydrogen tank. A value for the failure of a TPRD of 2.2×10^{-3} may therefore be used as a conservative upper limit. If more data become available in the future, the actual probability of failure can be better calculated.

5.5.2 Not opening of the TPRD in the event of fire

In the event of a fire in a hydrogen tank, there is a possibility that the TPRD will not open. The main cause of this failure to open is the local exposure of the hydrogen tank to a fire (Ruban et al, 2012; Ehrhart et al, 2020). If the local exposure to a fire takes place at some distance from the TPRD, the temperature rise in the vicinity of the TPRD may be insufficient to activate the device. As a consequence, the fire has the opportunity to damage the hydrogen tank, because the composite material at the heated area of the hydrogen tank can no longer bind the carbon fibre. As a result, the hydrogen tank loses its strength and will burst.

However, in literature, the possibility of local exposure to fire is disputed, because:
> hydrogen tanks are surrounded by the body of the hydrogen car;
> the probability is considered negligible that a tank of less than one metre will be locally exposed to a fire;
> pool fires spread and have no local character;
> a local fire at the car (for example in a tyre) will spread quickly to the entire car (Ehrhart, 2020).

In the case of a hydrogen car that has toppled onto its side, local exposure to a fire is possible, but given the low speeds in a parking garage, the probability is negligible (see footnote 6).

From several incidents involving CNG tanks it is known that the PRD failed to function due to a system blockage (Sunderland, 2008) or because the PRD responded too slowly (NHTSA, 2010). It is not clear to what extent these causes of failure apply to TRPDs in hydrogen tanks, because the precise functioning and layout of the TPRDs in the current generation of hydrogen cars is unknown:
> If the TPRD reacts at 110 °C, the mechanism of the TPRD must ensure that the supply of hydrogen from the hydrogen tank is possible. For this purpose springs or pistons are used that may fail to function or to function effectively, due to corrosion or dirt (Heise, 2014). It is unknown whether this failure mechanism is possible in the current TPRDs.
> The current TPRDs on hydrogen tanks consist of a glass bulb filled with liquid (De Vos, 2021; Dijkhof, 2021). This type of TPRD responds more quickly to a temperature rise than TPRDs based on a melting fuse.

> The outflow opening of a TPRD is a small pipe sealed off with a cap (De Vos, 2021) or a sticker (Dijkhof, 2021). This keeps dirt and moisture out, but does not block the outflow of hydrogen.[19]

As previously indicated, little data is available in literature about the probability of failure of TPRDs. Because there are so many uncertainties[20] and values for probability of failure suggest a degree of certainty that it not present, there is a clear preference in literature for uncertainty areas. This principle is applied to the statistical determination of the probability of failure of TPRDs (Ehrhart, 2020). In five different studies between 2006 and 2017, a total of sixteen hydrogen tanks were fully exposed to fire. The TPRDs on these hydrogen tanks were activated in all tests and operated as intended. On that basis, the statistical uncertainty distribution shown in Figure 5.1 was derived.

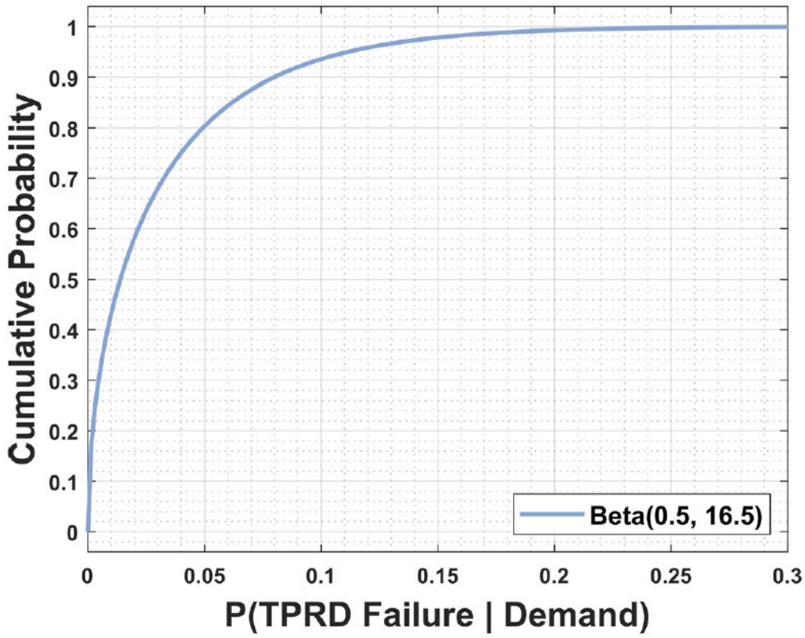

Figure 5.1 Uncertainty distribution for the odds that the TPRD will fail when activated.

On the basis of the above data, the odds of failure of the TPRD are always 0.3 or lower. In other words: the odds that '*the odds of failure of the TPRD on demand'* is 0.3 or smaller are equal to 1. If the certainty is allowed to be not 100% (1) but 99% (0.99), *'the odds of the failure of the TPRD on demand'* are smaller, namely 0.2. And with a certainty of 94%, *'the odds of the failure of the TPRD on demand'* is 0.1 at the most.
These figures must be seen as an indication, since the number of experiments is limited, and the hydrogen tanks and TPRDs from the period 2006-2017 may no longer be representative for today's standards. By applying large uncertainty intervals, the figures become higher than they are in reality, but on the other hand the figures are robust and would change little, if for example a TPRD were to fail in a future experiment.
For a safety measure like a TPRD, the statistical approach described above results in a non-realistic value. It is to be expected that the 95% reliability interval for the failure of the TPRD will become narrower, and far lower, as soon as more data become available in the future. Until that time, it will be necessary to consider for each situation (for example for a risk

19 Please note: the outflow opening of a TPRD must not be confused with the opening in the TPRD that opens as soon as the TPRD is activated.

20 Examples of uncertainties are the type of TPRD, the age of the TPRD, the maintenance regime, the availability and validity of data, etc.

analysis) whether and how the statistical approach above can be employed, and what probability of failure for a TPRD can be applied, on that basis.

5.6 Ignition

The probability of ignition is the sum of the probability of immediate ignition and the probability of delayed ignition. The probability of ignition is a value between 0 and 1. It is very difficult to determine the ignition probability for hydrogen. Sufficient data are often missing and the data that are available are often incomplete (Moosemiller, 2011). In 2015, for example, the Health and Safety Laboratory suggested that on the basis of the available literature about flammable substances, no probabilities of immediate ignition of hydrogen could be found (HSL, 2015).

In the absence of sound data, attempts have been made in literature to develop formulae to calculate the probabilities of immediate ignition and delayed ignition (Moosemiller, 2011). The outcomes of these formulae are an approximation and can only be seen as an indication.
The most common cause of ignition is static discharge, for example from a spark (HSL, 2008). The probability of static discharge is related to the energy that is released and relates to parameters such as process pressure and outflow speed. The more energy that is released, the greater the probability of immediate ignition. The probability of static discharge is calculated using formula 5:

$$P_{static\ discharge} = 0.0024 \times \frac{(P^{1/3}}{(MOE)^{2/3}} \qquad [5]$$

Where:
P = pressure in psi (1 psi = 0.069 bar)
MOE = minimum ignition energy in mJ

Figure 5.2 is a graphic representation of the formula, whereby the process pressure is converted from psi to bar and a minimum ignition energy of 0.019 mJ is assumed. At a process pressure of 700 bar (≈ 10,000 psi), according to this formula, the probability of immediate ignition is quite large, namely 0,73.

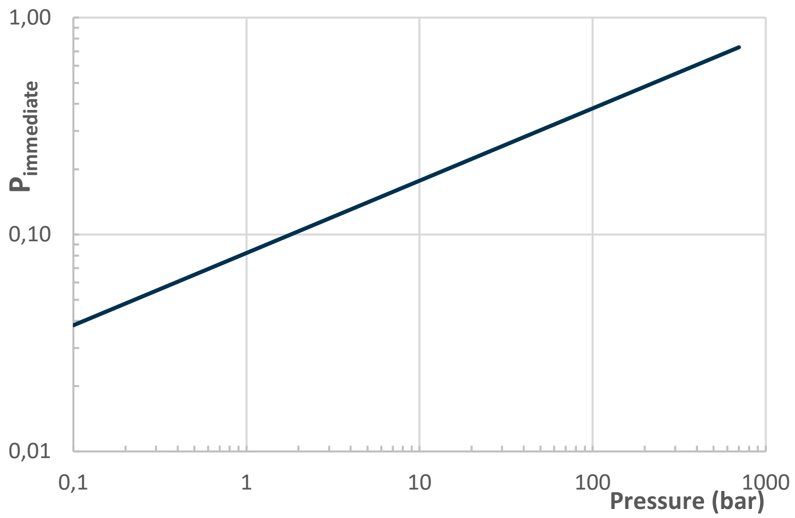

Figure 5.2 Probability of immediate ignition as a function of process pressure.

Research into incidents in the process industry in which hydrogen has released shows that in 4 of the 81 incidents, there was delayed ignition. Of the remaining 77 incidents, it is assumed that hydrogen was ignited immediately (Astbury et al, 2007).[21] These figures from the process industry must be seen as an indication because it is very questionable to what extent the systems in the process industry can be seen as analogons for hydrogen tanks.

The above studies suggest that in the event of the release of hydrogen under high pressure, there is a relatively high probability of immediate ignition. On the other hand, in HyRAM (software developed by Sandia National Laboratories), lower values are employed for the probabilities of immediate and delayed ignition, see Table 5.1 (Groth et al, 2015). A database from DNV is used as the basis for these figures, and shows that the probability of ignition for hydrocarbons is 0.01 at outflow rates of less than 1 kg/s. On this basis, ignition probabilities were derived for hydrogen, for HyRam, whereby use was made of the differences and similarities between hydrogen and methane (Tchouvelev et al, 2006).

Table 5.1 Probabilities of ignition for hydrogen in HyRam (Groth et al, 2015).

Flow rate (kg/s)	$P_{immediate}$	$P_{delayed}$
< 0.125	0.008	0.004
0.125 - 6.25	0.053	0.027
>6.25	0.230	0.120

Fuels such as petrol and diesel do have a probability of immediate ignition, but no probability of delayed ignition. The probability of immediate ignition for petrol is 0.065 and for diesel 0.01 (RIVM, 2021). The major differences in literature for the ignition probabilities of hydrogen raise question marks and mean that a comparison with the ignition probabilities of fuels is not possible. Further literature study will be needed to gain a greater insight into the determination and assumption of the ignition probabilities of hydrogen.

[21] The fact that the database contains 0 hydrogen incidents without ignition does not mean that those incidents did not take place. Because no effects were observed, such incidents cannot be included in the database.

5.7 Summary

Data collected in this chapter provide no certainty in absolute terms about the probabilities and odds of the release of hydrogen from a hydrogen car. As long as hydrogen cars are uncommon leading to the absence of sufficient empirical data, assumptions and data relating to other comparable systems will remain necessary. In this study, those comparisons and assumptions were made by comparing hydrogen cars with conventional cars. The results of these comparisons are shown in Table 5.2 and must be seen as indicative.

Table 5.2 Comparison of hydrogen car and conventional car

Occurrence	Probability or odds of hydrogen cars compared to conventional cars
Collision	Equal
Fire	Smaller
Release of fuel	Smaller or equal
Activation and failure of TPRD	N/A
Ignition	Uncertain

The conclusion is that on the basis of the collected data, the probability of hydrogen released in a parking garage is not greater - and is probably in fact smaller - than the probability that fuel will be released in a parking garage. On the other hand, the ignition probability of hydrogen appears to be greater than that for fuels such as petrol and diesel, but because the literature shows major discrepancies, it is not wise to issue any statements on the ignition probabilities of hydrogen. Any such statements will require more and thorough research, whereby the circumstances in which the experiments are held will have to be compared.

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[22] This article applies to residential areas, but is often also used for parking garages.

[23] The HyRAM technical manual refers to a publication that is available online (A. V. Tchouvelev. (2006). Risk assessment studies of hydrogen and hydrocarbon fuels, fuelling stations: Description and review, *International Energy Agency Hydrogen Implementing Agreement Task 19*). The author's publication, cited here, which explains how the odds of ignition for hydrogen are derived has indeed been traced.

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